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DEVELOPMENT OF A HIGH TEMPERATURE SILICONE BASE FIRE-RESISTANT HYDRAULIC FLUID

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A candidate silicone-base fire-resistant hydraulic fluid designated Nadraul HS-6 has been developed for future military aircraft hydraulic system design. The lubricating ability of this fluid has been demonstrated in hydraulic pump-loop circuit evaluations at 20.7 MPa (3000 PSI) and 55.2 MPa (8000 PSI) fluid pressures and at a fluid temperature as high as 163C (325F). Chemical and physical properties have been determined to establish both specification and hydraulic system design criteria and are reported herein.

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SUMMARY

INTRODUCTION

Aircraft fires pose a threat to human life and increase vulnerability of military aircraft during combat. A contributing factor to this hazard has been the use of a highly flammable petroleum base hydraulic fluid MIL-H-5606. Failure of hydraulic components due to improper maintenance procedures, fatigue, projectile damage, etc., can result in escaping fluid coming in contact with an ignition source such as a hot surface (engine, brakes), thus posing a fire hazard. Incidents of aircraft damage and loss due to hydraulic fluid induced fires have been documented by the Naval Safety Center (see Appendix A) as well as other military services. Thus, the need for the development of a safer fire-resistant military aircraft hydraulic fluid is immediately evident.

RESULTS

1. A candidate wide temperature range -54C (-65F) to 204C (400F) fire-resistant military aircraft hydraulic fluid designated Nadraul MS-6 has been developed. The formulation consists of tetrachlorophenylmethyl siloxane fluid containing 4 wt. % of dibutyl chlorendate as an anti-wear additive.

2. Hydraulic pump-loop circuit evaluations on Nadraul MS-6 have been conducted at 20.7 MPa (3000 PSI), 149C (300F) and 55.2 MPa (8000 PSI), 163C (325F) for 500 hours of operation.

3. The properties of Nadraul MS-6 at atmospheric pressure which differ from MIL-H-5606 and thus may require system redesign are:

a. Viscosity:	280% higher at 38C (100F) 225% higher at 93C (200F) 185% higher at 149C (300F) 163% higher at 204C (400F)
b. Density:	22% higher at 38C (100F) 22% higher at 93C (200F) 22% higher at 149C (300F) 22% higher at 204C (400F)
c. Bulk Modulus (Isothermal Secant)	28% lower at 38C (100F) 29% lower at 93C (200F) 28% lower at 149C (300F) 28% lower at 204C (400F)
d. Specific Heat:	18% lower at -18C (0F) 22% lower at 38C (100F) 26% lower at 93C (200F) 28% lower at 149C (300F) 30% lower at 204C (400F)

e. Thermal Conductivity: 6.7% higher at 38C (100F)
3.8% higher at 93C (200F)
1.6% higher at 149C (300F)
2.4% lower at 204C (400F)

f. Coefficient of Cubical (Thermal) Expansion:
29% lower in the temperature range from 38C (100F) to 149C (300F)

4. The advantageous properties of Nadraul MS-6 relative to MIL-H-5606 are:

a. Substantially improved fire-resistance

b. Higher temperature capability

c. Significantly lower vapor pressure

d. Slightly higher thermal conductivity up to 140C (300F)

e. Shear stability

5. The disadvantageous properties of Nadraul MS-6 relative to MIL-H-5606 are:

a. Reduced bulk modulus

b. Increased density

c. Lower specific heat

d. Increased foaming tendency (can be controlled with anti-foam additive)

e. May corrode mild steel in the presence of copious quantities of water (10,000 PPM) under certain conditions.

f. High cost.

CONCLUSIONS

The development of a significantly improved fire-resistant hydraulic fluid for use in current military aircraft without requiring retrofit modifications has been shown to be a formidable task. In order to achieve superior fire-resistance properties in a candidate fluid other critical properties such as viscosity, density and bulk modulus will probably be quite different when compared to the currently used petroleum fluid (MIL-H-5606). Because of these differences, the new fluid will not function properly in current hydraulic system designs. New fluids which are similar to 5606 in basic physical properties usually offer only modest improvements in fire-resistance characteristics. Accordingly, the major thrust of this program has been directed toward the development of a military aircraft hydraulic fluid with excellent fire-resistance properties suitable for use at operating temperatures as high as 177 to 284C

(350 to 400F) in future aircraft design. For this purpose, a candidate fluid designated Nadraul MS-6 has been developed based on a tetrachlorophenylmethyl siloxane fluid incorporating dibutyl chlorendate as an antiwear additive. From previous work with silicone fluids, it has been found that the properties of this fluid, which are significantly different from the currently used hydraulic fluid and which will have the greatest effect on system performance, are its viscosity, density, and bulk modulus. Future military aircraft hydraulic systems will have to be designed to accommodate these differences in properties in order to take advantage of the fluid's fire-resistant nature. Whether such redesign is practical without undue penalties in other critical areas remains to be determined as the next step toward the advancement of fire-resistant military aircraft hydraulic systems. To this end limited testing is planned for the near future on component redesign required for the use of Nadraul MS-6 in 55.2 MPa (8000 PSI) hydraulic systems, under AIRTASK A3400000/001C/9W058601, Lightweight Hydraulic System (LHS) Development.

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BACKGROUND

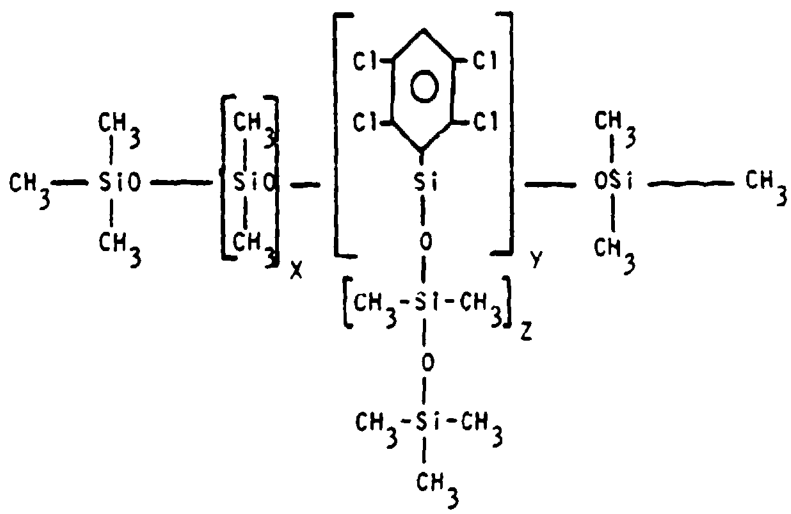
A replacement for MIL-H-5606 hydraulic fluid has been sought by the military services for the past thirty years in order to minimize or eliminate potential fire hazards. In the early 1950's, the U. S. Navy converted a limited number of aircraft to a water-glycol fluid and experienced difficulties due to poor low temperature properties, excessive corrosion and an upper temperature limit of only 93C (200F). In addition, loss of the water through evaporation resulted in a flammable fluid. Phosphate esters developed during the late 1940's are currently used in commercial aircraft and would require retrofit of elastomeric components and reconfiguration of electrical insulation. In addition, maximum useful temperature is limited to 107C (225F). In 1966, the U. S. Air Force developed a fluid based on super-refined mineral oil for restricted use in Southeast Asia. It was not suitable for use below -7C (20F).

Military aircraft hydraulic systems have been designed around the properties of MIL-H-5606 fluid so that the use of replacement fluids not identical in properties could cause degradation in system performance. The exact nature and degree of system degradation was not quantified until the U. S. Navy, in 1974, evaluated a silicone formulation in a flight control simulator (iron-bird analysis). The impetus for the investigation centered on the fact that the U. S. Air Force, in the late 1960's, developed a candidate fluid based on the polymerization of alpha-olefins (MIL-H-83282) and designated synthetic hydrocarbon fluid. This fluid possessed similar properties to MIL-H-5606, with the exception of increased temperature capability and improved anti-wear and fire-resistance properties. In addition, it was proved functional in a single Navy F4J flight test and later in F-4 squadron tests. It was envisioned by the U. S. Navy that the MIL-H-83282 fluid would serve as an interim fluid pending the development of the more fire-resistant silicone fluid. However, it was also felt that the interim fluid could be eliminated if the silicone fluid program proceeded at an accelerated pace. This led to the development of Nadraul MS-5 (1), (2) which was evaluated in the flight control simulator (3), (4). The properties of MS-5 which were significantly different from MIL-H-5606, in addition to enhanced fire-resistance capability, included increased viscosity (three-fold at 38C (100F) and 99C (210F)), increased density (25 percent at 25C (77F), and reduced isothermal secant bulk modulus (14 percent at 99C (100F), 20.7 MPa (3000 psi)). The effect of these differences on the performance of a currently designed military aircraft hydraulic system was then evaluated. The results indicated that the MS-5 fluid could be flight tested in the main hydraulic systems of the F-4 aircraft but usage in the utility system would require major retrofit because of viscosity/density effects. The degradation due to its lower bulk modulus was not as detrimental as previously thought. The U. S. Navy then decided to authorize the use of MIL-H-83282 in current Navy aircraft and redirected the development program on silicone fluid toward its use in new hydraulic system designs. The U. S. Army has also authorized the use of MIL-H-83282 in its aircraft fleet, while the U. S. Air Force has most recently (June 1976) embarked on a new program to develop a nonflammable hydraulic fluid for future system designs. They have rejected the use of MIL-H-83282 because of its marginal fire-resistance improvement compared to MIL-H-5606 and increased low temperature viscosity which they feel will limit U. S. Air Force aircraft missions.

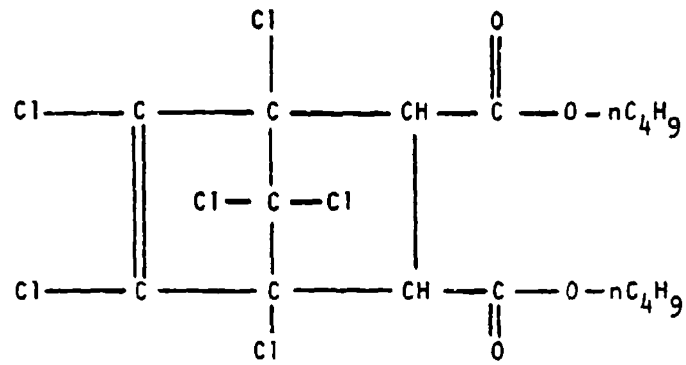
The previously developed Nadraul MS-5 silicone fluid, although possessing improved fire-resistance and anti-wear properties, was limited to application temperatures not greater than 135C (275F) due to the thermal instability of the sulfur-containing thiadiazole anti-wear additive. Therefore, MS-5 could not be considered as a high temperature 204C (400F) fluid. In addition, it was determined that the supplier of the base fluid, a dichlorophenylmethyl siloxane, had taken this product off the market because of low-volume usage. Faced with these problems, it was decided to investigate the use of a tetrachlorophenylmethyl siloxane fluid, which had been considered in the previous program but was rejected because it would immediately precipitate the viscosity index improver found in MIL-H-5606, when admixed.

The tetrachlorophenylmethyl siloxane base fluid, which is used in the constant speed drives on the A-4 aircraft, is covered by military specification, MIL-S-81087A. Because of the increased chlorine content relative to the dichlorophenylmethyl siloxane fluid, the inherent anti-wear properties are improved, however, the use of an anti-wear additive was still required. Dibutyl chlorendate was found to provide the desired anti-wear qualities even at temperatures as high as 204C (400F). The optimum formulation resulting from this investigation contained 4 wt. percent dibutyl chlorendate in tetrachlorophenylmethyl siloxane and is designated Nadraul MS-6.

The chemical structures of the base fluid and antiwear additive are shown below:



Tetrachlorophenylmethyl Siloxane



Dibutyl Chlorendate

Having established a suitable formulation based on anti-wear properties, additional property determinations were made.

R E S U L T S A N D D I S C U S S I O N

The final phase of this program centered on developing design guide data on a 30 dm^3 (eight gallon) batch of Nadraul MS-6. In addition to evaluations for specification type properties, this batch of fluid was used to generate data which are not usually found in specifications for hydraulic fluids but are essential for the design and analysis work involved in developing new hydraulic systems. These properties include viscosity-pressure variations, density-temperature variations, bulk modulus and heat transfer characteristics. Also an evaluation of fluid performance in a 55.2 MPa (8000 PSI) hydraulic system test stand was performed.

HYDRAULIC FLUID PROPERTIES CRITICAL FOR SYSTEM DESIGN

Viscosity

This property of a fluid is a meausre of it's resistance to flow and varies with temperature and pressure. In designing hydraulic systems a balance must be achieved between high and low viscosity characteristics. From a lubrication standpoint, a moderately high viscosity is desirable in order to keep mating surfaces separated and thus minimize wear. This also favors less internal leakage. On the other hand, in order to obtain a rapid response of the flight control system, it is desirable to keep the viscosity as low as possible. Table I shows a comparison of the kinematic viscosities of MIL-H-5606, MIL-H-83282 and Nadraul MS-6 as a function of temperature and pressure. The viscosity of MS-6 fluid is appreciably higher than MIL-H-5606 and MIL-H-83282 but as temperature and pressure increase the magnitude of the differences becomes smaller.

The values for the viscosity at elevated pressure of MIL-H-5606 and MIL-H-83282 were obtained from reference 5. The data for Nadraul MS-6 was calculated using equation {1}.

$$\mu_p = \mu_o e^{\alpha P} \qquad \{1\}$$

where μ_p = absolute viscosity at pressure

μ_o = absolute viscosity at atmospheric pressure

P = pressure

α = pressure coefficient (6) (7)

α 38C (100F) = 1.28×10^{-4}

α 93C (200F) = 0.96×10^{-4}

α 149C (300F) = 0.38×10^{-4}

Density

Fluid density is not only important from a system weight standpoint but is also a critical parameter used in the analyses of Reynolds number, bulk modulus and orifice flow. Table 2 shows the variation of density with temperature and pressure for the three fluids under discussion. The density of Nadraul MS-6 was determined experimentally at 38C (100F), 93C (200F), 149C (300F) and 204C (400F). The density of Nadraul MS-6 as a function of pressure was obtained using equation {2}.

$$\rho = \frac{\rho_o}{1 - \frac{P}{(B_{IS})_P^t}} \qquad \{2\}$$

where:

ρ = density at pressure

ρ_o = density at atmospheric pressure

P = pressure

$(B_{IS})_P^t$ = isothermal secant bulk modulus at temperature t and pressure P

The density of MS-6 is approximately 20-25% higher than either MIL-H-5606 or MIL-H-83282 at the temperatures and pressures studied.

Bulk Modulus

The bulk modulus of a fluid, which is the reciprocal of its compressibility is an important property in the design of hydraulic systems.

Ideally, a high bulk modulus (low compressibility) is desirable since this results in a more stable and less elastic system. Four bulk moduli values have been defined based on the volume change of a fluid with pressure and temperature. They are:

1. Isothermal Secant
2. Isothermal Tangent
3. Adiabatic Secant
4. Adiabatic Tangent

The secant modulus is an average modulus and can be thought of as the average pressure required to produce a given volume change per unit volume over a given pressure range while the tangent modulus represents the bulk modulus at a specific temperature and pressure. Isothermal refers to condition of constant temperature while adiabatic refers to conditions of no heat gain or loss in the system (constant entropy). Selection of the proper modulus for a particular design application is dependent upon the function performed and the pressure excursion experienced. Functions that occur rapidly require adiabatic moduli while those that occur slowly with no temperature change require isothermal moduli. Large pressure changes require the use of secant moduli while small pressure fluctuations require the use of tangent moduli. The combination of function and pressure excursion dictates which of the four bulk modulus values will be most meaningful for design criteria.

The isothermal secant bulk modulus of Nadraul MS-6 as a function of pressure was determined in the Klaus apparatus (8) at 38C (100F). The following values of bulk moduli were obtained:

Pressure MPaG (PSIG)	Isothermal Secant Bulk Modulus MPaG (PSIG)
13.8 (2000)	966 (146,000)
27.6 (4000)	1090 (158,000)
41.4 (6000)	1173 (170,000)
55.2 (8000)	1256 (182,000)
69.0 (10,000)	1339 (194,000)

From these data points the isothermal tangent, and adiabatic secant and tangent moduli of Nadraul MS-6 were then calculated.

Using equation {3}, the isothermal secant bulk modulus at 38C (100F) and atmospheric pressure was calculated.

$$(B_{IS})_P^t = (B_{IS})_o^t + 6P \qquad \{3\}$$

where:

$(B_{IS})_P^t$ = isothermal secant bulk modulus at pressure P and temperature t

$(B_{IS})_o^t$ = isothermal secant bulk modulus at atmospheric pressure and temperature t

P = pressure

$(B_{IS})_o^{38C\ (100F)}$ was found to be 925 MPaG (134,000 PSIG). With this calculated value, $(B_{IS})_o^t$ was then obtained for temperature of 93C (200F), 149C (300F) and 204C (400F) using equation (4).

$$\log\ (B_{IS})_o^{t_1} - \log\ (B_{IS})_o^{t_2} = \beta\ (t_2 - t_1) \qquad (4)$$

where β is a relationship of the slope as a function of pressure as shown below:

Pressure MPaG (PSIG)	$\beta \times 10^3$
0 (0)	1.40
6.9 (1000)	1.28
13.8 (2000)	1.19
20.7 (3000)	1.11
27.6 (4000)	1.04
34.5 (5000)	0.973
41.4 (6000)	0.919
48.3 (7000)	0.871
55.2 (8000)	0.823
62.1 (9000)	0.789
69.0 (10000)	0.754

The isothermal secant bulk modulus values at 20.7 MPaG (3000 PSI) and 55.2 MPaG (8000 PSIG) were then calculated from equation (3) for each of the above temperatures.

The isothermal tangent bulk modulus was calculated from the isothermal secant bulk modulus using equation (5).

$$(B_{IT})_P^t = (B_{IS})_{2P}^t \qquad (5)$$

where:

$(B_{IT})_P^t$ = isothermal tangent bulk modulus at temperature t and pressure P

The relationship between the isothermal tangent bulk modulus and adiabatic tangent bulk modulus is given in equation (6):

$$(B_{IT})_P^t = (B_{AT})_P^t \;/Zt \qquad \{6\}$$

where:

$(B_{AT})_P^t$ = adiabatic tangent bulk modulus at temperature t and pressure P

Z_t = C_P/C_V at temperature t

C_P = specific heat at constant pressure

C_V = specific heat at constant volume

Since data was not available for C_V, Zt was calculated using equation {7} (9).

$$Z_t = \cfrac{1}{1 - \cfrac{TV\alpha^2(B_{IT})_P^t}{C_P}} \qquad \{7\}$$

where:

T = absolute temperature
V = specific volume
α = thermal expansivity

The following values of Z were obtained using equation {7}:

Temperature	Z
38C (100F)	1.184
93C (200F)	1.147
149C (300F)	1.119
204C (400F)	1.094

The adiabatic secant bulk modulus was obtained from the adiabatic tangent bulk modulus using equation {8}.

$$(B_{AS})_{2P}^t = (B_{AT})_P^t \qquad \{8\}$$

where:

$(B_{AS})_{2P}^t$ = adiabatic secant bulk modulus at temperature t and pressure 2P

Tables 3 through 6 list the bulk moduli for MIL-H-5606, MIL-H-83282 and Nadraul MS-6 at atmospheric pressure, 20.7 MPaG (3000 PSIG) and 55.2 MPaG (8000 PSIG) and from 38C (100F) to 204C (400F). The bulk modulus of Nadraul MS-6 is lower than MIL-H-5606 or MIL-H-83282 indicating the higher degree of compressibility associated with polysiloxane fluids.

Specific Heat

The specific heat of a fluid is a measure of the amount of heat a given quantity of fluid can absorb from its environment. Generally, a distinction is made as to whether this measurement is at constant pressure or constant volume. Because liquids are relatively incompressible compared to gasses there is little difference between the two values. It is common practice to determine the specific heat of liquids at constant pressure.

For a given hydraulic system supplying a given quantity of heat to the hydraulic fluid, a liquid with a high specific heat will undergo a smaller temperature rise than will a liquid with a low specific heat. Thus a high value aids in maintaining a lower operating temperature in a system and in some applications increases the amount of heat that may be removed from a system hot spot without causing degradation of the fluid.

Table 7 shows the specific heat of MIL-H-5606, MIL-H-83282 and Nadraul MS-6 from -18C (0F) to 204C (400F). The MS-6 fluid is shown to be lower than the other two fluids.

Thermal Conductivity

Thermal conductivity is a measure of the ability of a material to transfer heat. Heat transfer in operating hydraulic systems is accomplished primarily by convection because of forced liquid mixing. However, thermal conductivity is of importance in the transfer of heat to or from physical boundaries of hydraulic systems. A liquid having a high thermal conductivity will more readily pick up heat in hot system components, such as valves and pumps and transfer it to cooler system components such as heat exchangers.

Table 8 shows the thermal conductivity of MIL-H-5606, MIL-H-83282 and Nadraul MS-6 from -18C (0F) to 204C (400F). At the lower temperatures the order of increasing thermal conductivity is MIL-H-5606 < Nadraul MS-6 < MIL-H-83282 while at the higher temperature 204C (400F) the order is reversed. In the temperature range 163C (325F) to 191C (375F) the thermal conductivity is approximately the same value for all three fluids.

Coefficient of Cubical (Thermal) Expansion

This coefficient is critical when hydraulic systems must operate over a wide temperature range. The designer must allow for adequate reservoir capacity especially in closed systemsto allow for fluid volume changes with temperature. A low coefficient of expansion will minimize the capacity required to accommodate volume changes. Average values for the coefficient of thermal expansion over the temperature range 38C (100F) to 149C (300F) for MIL-H-5606 and MIL-H-83282 are $8.6 \times 10^{-4} \frac{1}{C}$ ($4.8 \times 10^{-4} \frac{1}{F}$) and $8.3 \times 10^{-4} \frac{1}{C}$ ($4.6 \times 10^{-4} \frac{1}{F}$) respectively. Table 9 shows the coefficient of thermal expansion for Nadraul MS-6 determined at specified temperatures. In the temperature range cited above, the average coefficient of thermal expansion for the MS-6 fluid is $8.5 \times 10^{-4} \frac{1}{C}$ ($4.7 \times 10^{-4} \frac{1}{F}$).

Hydraulic Fluid Properties (General)

This section deals with those properties of an aircraft hydraulic fluid which are important in the selection of a fluid but are usually not required in system design considerations.

Fire Resistance

Although many flammability tests have been developed and standardized over the years they lack for the most part a significance to "real-world" fire hazards. Even those that attempt to simulate a prototype fire hazard environment can give misleading results. In this program, the philosophy has been to perform as many different flammability tests as possible and then determine which candidate fluid provides the best overall degree of fire resistance in most of the tests. Table 10 summarizes the flammability test data that have been obtained on MIL-H-5606, MIL-H-83282 and Nadraul MS-6. One anomalous trend can be seen in the tests using a hot manifold surface as the ignition source in that MIL-H-5606 ignites at a higher temperature than the other fluids. The apparent reason for this behavior is the fact that MIL-H-5606 is more volatile than the other fluids and thus evaporates before reaching the hot surface. When ignition does occur the flame propagates to the pool of fluid that has formed in the bottom of the test unit. On the contrary the other fluids self-extinguish after ignition.

One of the major causes of military aircraft hydraulic fluid fires is fluid escaping onto hot surfaces which are lower in temperature than the ignition point of MIL-H-5606 in the hot manifold test. Obviously then this test does not simulate actual fire hazard conditions.

Flash and fire points can also be misleading. A good example can be found with phosphate ester type fluids some of which have flash and fire points as low as 171C (340F) and 182C (360F), respectively, yet exhibit in other flammability tests marked degrees of fire retardancy. The phosphate esters are unique in that they readily decompose on heating and it is these decomposition products which are ignited. If the residence time of the fluid in the ignition source is of such a short duration that decomposition does not occur to any appreciable extent then the fluid may not burn, as is found in the high pressure spray test.

Some flammability tests performed on hydraulic fluids were originally designed to test the flammability properties of jet fuel. For instance, the flame propagation induction period test and the mist flashback test are two examples. As such, they were designed to differentiate flammability properties of fluids that burn readily to begin with. Their application to fluids which are fire resistant may be questionable.

Another area of flammability testing involves the evaluation of fluids subjected to incendiary ammunition fire. It appears that any time this test is attempted the conditions usually are varied by those setting up the test, thus, this type of testing has not been standardized. The results of one such test that was performed on MIL-H-5606, MIL-H-83282 and Nadraul MS-5 (similar to Nadraul MS-6) are given in Table 11. Since consistent fluid sprays are difficult to reproduce by impacting liquid containers with projectiles, the fluid to be tested was forced through a small orifice at a pressure of 6.9 MPa (1000 PSI). An incendiary bullet was then fired at a striker plate located in the vicinity of the fluid spray. Motion pictures were used to record the results of all attempted ignitions. The results in Table 11 show the improved fire-resistance properties of the silicone fluids compared to petroleum and synthetic hydrocarbon fluids. Again it should be pointed out that the significance of this test to "real-world" aircraft fire hazards is unknown.

Another case of hydraulic fluid ignition in aircraft is fluid coming in contact with an electrical arc which resulted from chafing of electrical wire bundles. No standardized test has been developed to evaluate fluids under these conditions.

Lubricity

A major criteria for determining the capability of a fluid to function as a hydraulic fluid is its ability to lubricate hydraulic pump components. Adequate lubricity is essential for the normal operation of aircraft hydraulic pump systems. Laboratory screening techniques such as the four ball wear tester were employed in the development of suitable anti-wear additives for silicone fluids. The most promising candidate fluids were then evaluated in a pump test. Table 12 summarizes the results of both laboratory and mechanical pump-loop circuit evaluations performed to date. In this final phase of the program, a pump test was performed on the MS-6 fluid at 55.2 MPa (8000 PSI). An on-going development effort by the Navy (Naval Air Development Center Fluid Systems Group) involves the use of high pressure hydraulic systems with benefits of reduced weight and volume (10). The current fluid selected for this study is MIL-H-83282. Since system redesign will be required for both programs (55.2 MPa (8000 PSI)), MIL-H-83282 - 20.7 MPa (3000 PSI) Nadraul MS-6) it was of interest to evaluate the MS-6 fluid in a mechanical pump-loop circuit at 55.2 MPa (8000 PSI).

Details concerning the operation of the mechanical pump-loop circuit evaluation along with photographs and schematic diagrams have previously been reported (11). A Rogers Hydraulic Inc. industrial high pressure piston pump model PF300 was selected for this evaluation. A high pressure aircraft piston pump was not readily available for this operation. The pump was disassembled and examined for condition prior to the start of the test and was found to be in excellent condition. Table 13 shows the operating data under which the evaluation was performed. From the very beginning of the test the return line filter had to be replaced rather frequently (see Table 14) because of high ΔP readings. No evidence of fluid degradation based on viscosity or anti-wear properties was found (see Table 15). There were two incidents which could have contributed to this problem. The first involved the deterioration of a composite cellulose bearing in the auxiliary pressure system. The second was related to the use of a plastic in-line flowmeter which deteriorated at the test temperature and was replaced with a glass version. The exact nature of this problem has not been determined although it is considered to be related to the temperature limitations of the materials involved and not a problem with the fluid.

After 400 hours of operation the pump was removed from the stand due to pressure loss from 55.2 MPa (8000 PSI) to 51.2 MPa (7450 PSI) and a drop in flow rate from 0.256 dm^3/s (4.1 GPM) to 0.231 dm^3/s (3.7 GPM) at a system operating temperature of 163C (325F). The pump was disassembled and examined. The seven pistons showed no signs of unusual wear. All of the piston shoes (Figure 1) exhibited slight feathering on the outer edges where the shoe contacts the wear plate. The shoe wear plate (Figure 2) had metal deposit buildup which was removed by polishing. The piston shoes were dressed to remove the feathered edges. All piston inlet ch valves appeared to operate and move freely. The cam to bearing wear plate (Figure 3) had a section of the surface missing indicative of spalling (Figure 4). No evidence of surface distress was found on the bearing. The wear plate was reversed when reassembled with the damaged surface facing the pump cam.

After exposure for several days to the atmosphere, corrosion was found on certain areas of the pump. These included the pump housing flange on the pump discharge port side (Figure 5), the pressure buildup side of the pump cam (Figure 6) and the cam to bearing wear plate where it contacted the pump cam (Figure 7). The corrosion was removed from all of these components and the pump was reassembled and mounted to permit removal of the ball stop port plugs so that the discharge port balls and springs could be examined. It was found that the spring lengths were from 0.40 mm (.016 in.) to 1.59 mm (.063 in.) shorter than the springs taken from an identical pump not subjected to this test. The pump manufacturer was consulted to determine the proper spring length and to determine corrective measures. It was suggested that the problem was faulty seating of the ball check valves and were advised that the ball could be tapped with a small hammer to reform the ball seat in the valve body. Prior to reforming the ball seat a hand drill was used to remove burrs being careful not to remove an excessive amount of material from the ball seat. The check valve balls were then examined for surface condition. Number 4 ball was a brown color and did not appear as shiny as the rest. Numbers 1, 2, 3, 5 and 6 balls also were brown in color but these were shiny. Number 7 ball had a light blue color which seemed to indicate an extreme temperature condition. Number 7 ball was replaced and the ball stops were installed and tightened to the proper torque. The pump was then reinstalled in the test circuit. The pump was started and operated for one hour when a pressure pulse photo was taken. The photo indicated a very erratic pressure pulse from several of the pistons. Pump operation was continued for an additional hour to determine if pump performance would improve by further seating of the ball check valves. No improvement was found so the pump was removed and disassembled again. The valve body of eacn piston discharge check valve was removed and replaced with a new part as were the check valve balls, springs and ball stops. The pump was reassembled and installed in the test stand and a break-in run of five hours was performed. After break-in the system was brought to full operating conditions and a pressure pulse photo taken which indicated a steady pressure discharge and normal functioning. An additional 100 hours of operation were obtained before the test was arbitrarily terminated. It should also be emphasized that this pump was run at it's upper temperature limit and thus may have contributed to some of the problems experienced during operation.

During the entire test a record was kept of the pump shaft seal leakage under dynamic conditions. The seal material normally supplied with this pump is BUNA N (nitrile). This was replaced prior to initiating the test with fluoroelastomer seals. No unusual seal leakage was observed. Less than 1 ml of fluid was collected during any one operating period (approximately 7 hours).

In regard to the selection of seals no one seal material is available which is useable over the temperature range of Nadraul MS-6. Programs are underway however which hope to solve this problem (12).

Volatility

The vapor pressure of a fluid is a measure of the ease with which the molecules of the liquid can escape from the surface and form a vapor. Hydraulic fluid with a high vapor pressure can result in system failure or component damage. Formation of vapor in control lines, actuators, servomotors and other components will adversely affect the operation of these components. Boiling on the suction side of the pump will reduce the pump delivery and cause cavitation. Table 16 compares the vapor pressure of the three fluids under discussion. Nadraul MS-6 is shown to exhibit an extremely low vapor pressure compared to MIL-H-5606 and MIL-H-83282 and at certain temperature levels the difference is several orders of magnitude.

GAS/LIQUID INTERACTIONS

Foaming

Foaming is undesirable in hydraulic systems since it can cause a loss of system efficiency, defective lubrication and loss of fluid by overflow of the foam. Air can be introduced into a hydraulic system from open reservoirs, leakage on the suction side of the pump, seal leakage or when filling the system. Table 17 shows that the foaming tendency of Nadraul MS-6 is significantly higher than either MIL-H-5606 or MIL-H-83282. The foam is quickly dispersed however within the 10 minute settling period required in MIL-H-5606 and MIL-H-83282.

The commonly used additives designed to control the foaming tendency of conventional oils were found to be completely ineffective when used in the MS-6 fluid. A further investigation (15) uncovered a perfluoroalkylpolyether (Krytox 143 AB) which was found to be exceptionally well suited for this purpose.

Two methods have been found to achieve the desired results. In the solvent addition method 1 g of a 2 wt. % solution of anti-foam agent in solvent (trichlorotrifluoroethane) is added to 200 g of MS-6 fluid to give a 100 ppm concentration of anti-foam agent in the hydraulic fluid. The mixture is then stirred for approximately 1 minute. In the direct addition method 0.02 g of anti-foam agent is added to 200 g of MS-6 fluid. The mixture is then heated for 10 minutes at 110C (230F) with stirring, and is allowed to cool to room temperature prior to testing. As can be seen in Table 17 the foaming tendency of MS-6 fluid is completely eliminated.

The mechanism of foam inhibition has been adequately presented in the literature (16). In general, foam inhibitors should be only slightly soluble in the base oil and are most effective at concentrations which slightly exceed their maximum solubility limit. Below this limit foam inhibitors can be initially effective only if present as insoluble droplets. However, with time the insoluble droplets, which function by spreading a surface film and collapsing the bubble that is formed, may desorb readily into solution so that the inhibiting action is lost. In the present investigation this was indeed observed at inhibitor concentrations below 100 ppm. The initial inhibition that was observed was gradually destroyed with aging (several days). Above 100 ppm concentration of anti-foam agent reduced foaming tendency is observed even after three weeks storage.

Gas Solubility

Hydraulic fluids, like other liquids, tend to dissolve any gases that may be in contact with them. The amount of gas dissolved by a particular liquid depends upon the composition of the gas, the composition of the liquid, the temperature, and the pressure. At room temperature and atmospheric pressure, between 5 and 15 percent air, by volume, can be found in solution in hydraulic fluids. A distinction should be made between dissolved gases and trapped or entrained gases. The dissolved gases have virtually no effect on the physical properties of the liquid. They become important only when they are evolved from solution in the form of bubbles creating a foam or a pocket of gas in the system. Once the gas has evolved from solution, the physical properties of the liquid-gas mixture are strongly influenced by the resulting foam.

The solubility of gases in liquids is generally considered to be inversely proportional to the temperature and directly proportional to the pressure. Log-log graphs of gas solubility vs. temperature are linear over moderate ranges of temperature.

The solubility of gases in Nadraul MS-6 was determined by ASTM D2780 for air and nitrogen. For air at 689 KPa (100 PSI) and 20C (70F) the

Ostwald coefficient is 0.17 while the Bunsen coefficient is 1.09. For nitrogen at 6.9 MPa (1000 PSI) and 20C (70F) the Ostwald coefficient is 0.11 and the Bunsen coefficient is 6.70. A direct comparison of these coefficients with MIL-H-5606 and MIL-H-83282 was not made. However, in general, the air solubility of silicone and petroleum fluids increases more rapidly with pressure than it does for the polar water base or phosphate ester fluids (17). However, at a pressure of 1 atmosphere the air solubility of petroleum oils is approximately 10% by volume while that of silicone fluids is approximately 24%.

Stability and Corrosiveness

Table 18 shows the stability and corrosiveness properties of Nadraul MS-6. The fluid is shown to be highly stable under the conditions of the particular test. The thermal stability test is based on the oxidation-corrosion test (FTS-791-5308) which was modified so that nitrogen gas was passed through the fluid instead of air. This eliminated any oxidation so the results were indicative of the thermal stability of the fluid. Tests were performed both in the presence and absence of metal coupons. In the oxidation-corrosion test it should be pointed out that the only metal specimen to show a significant weight change was copper at 177C (350F) and 204C (400F). Normally this test which is an accelerated test, is run for only 72 hours at elevated temperatures as opposed to the 168 hours shown in Table 18.

As reported in reference 14 testing of Nadraul MS-6 with added water (10,000 PPM) in the presence of AISI 1010 steel showed corrosion of the strip after 1 cycle (8 hours at 104C (220F), 16 hours at room temperature) of thermal exposure. In the absence of added water no corrosion was found after 10 cycles. Further studies with the individual chemical components of Nadraul MS-6 showed similar results.

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FIGURE 1. PISTON SHOES

FIGURE 2. SHOE WEAR PLATE

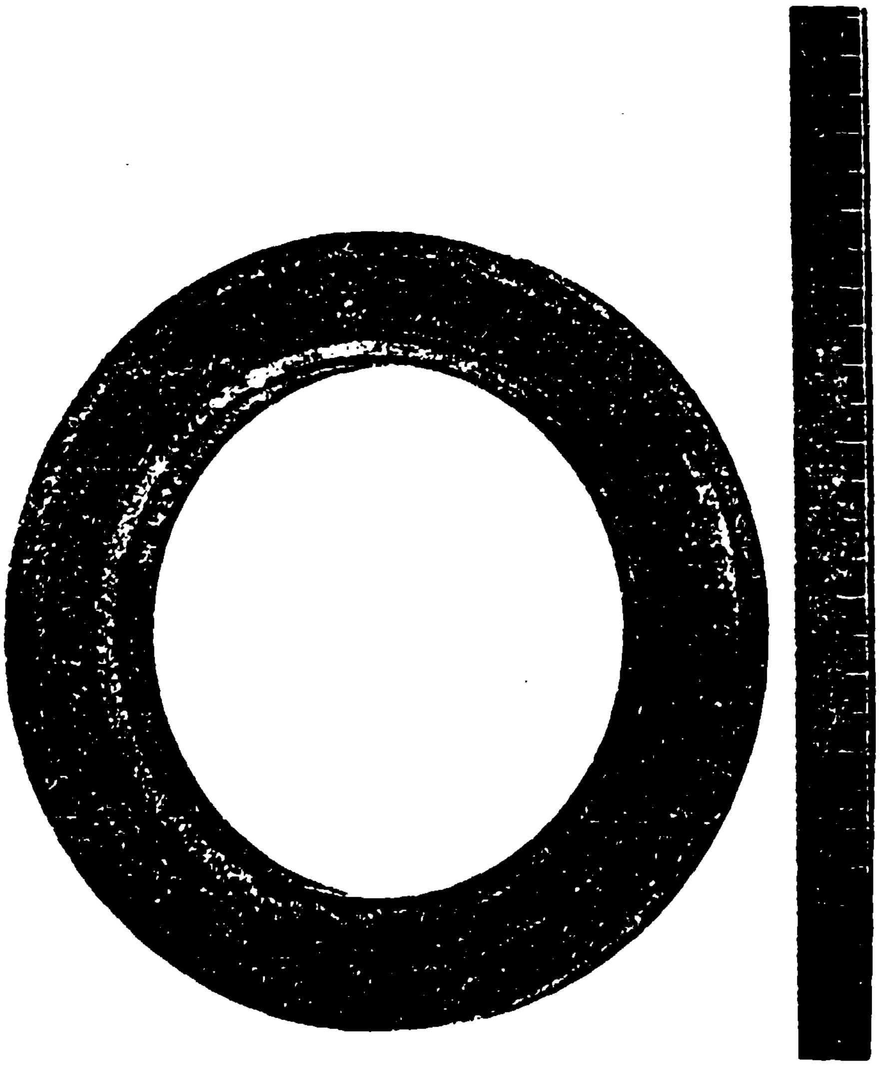

FIGURE 3. CAM TO BEARING WEAR PLATE

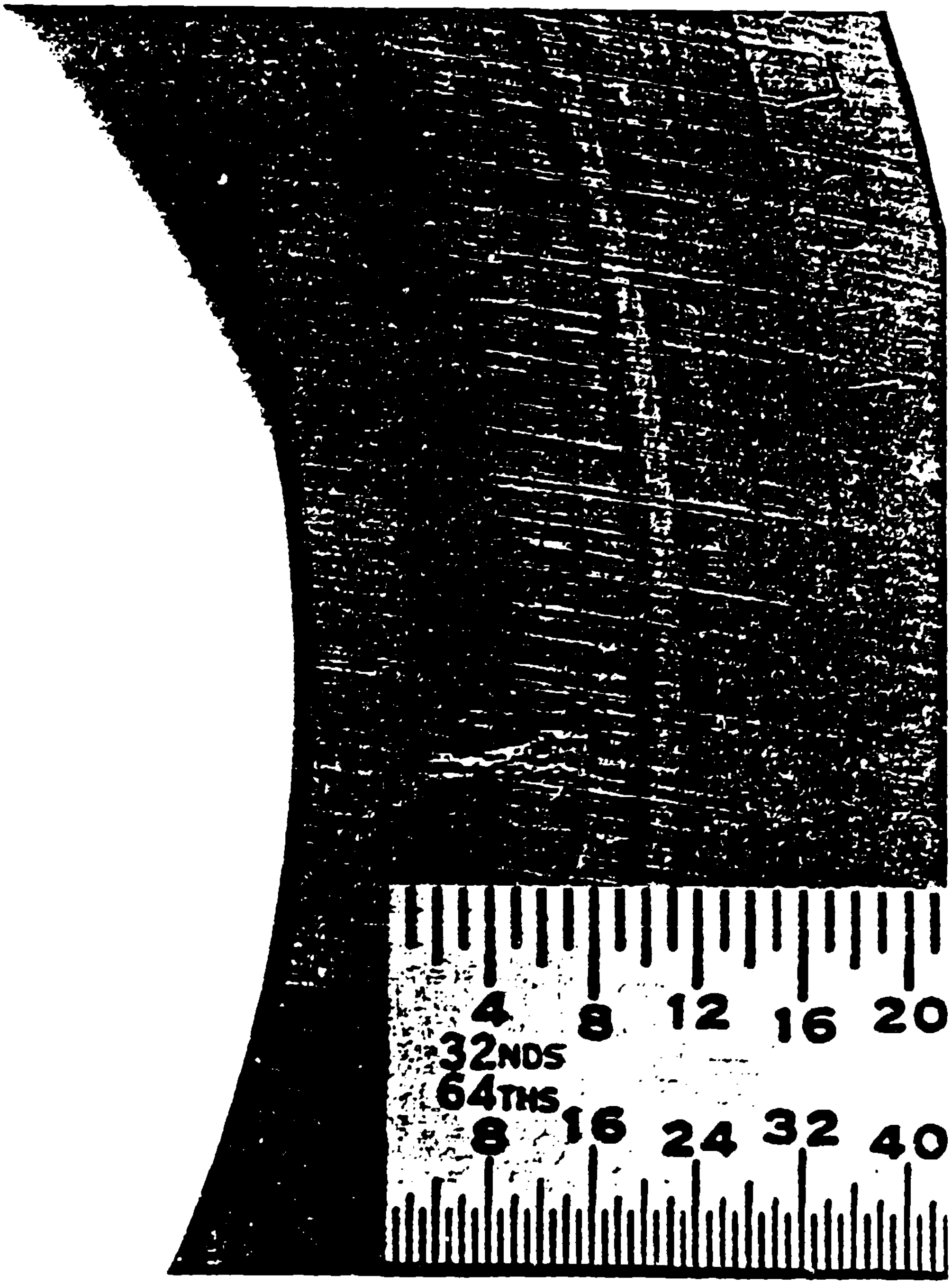

FIGURE 4. MAGNIFIED VIEW OF SPALLING FOUND ON CAM TO BEARING WEAR PLATE

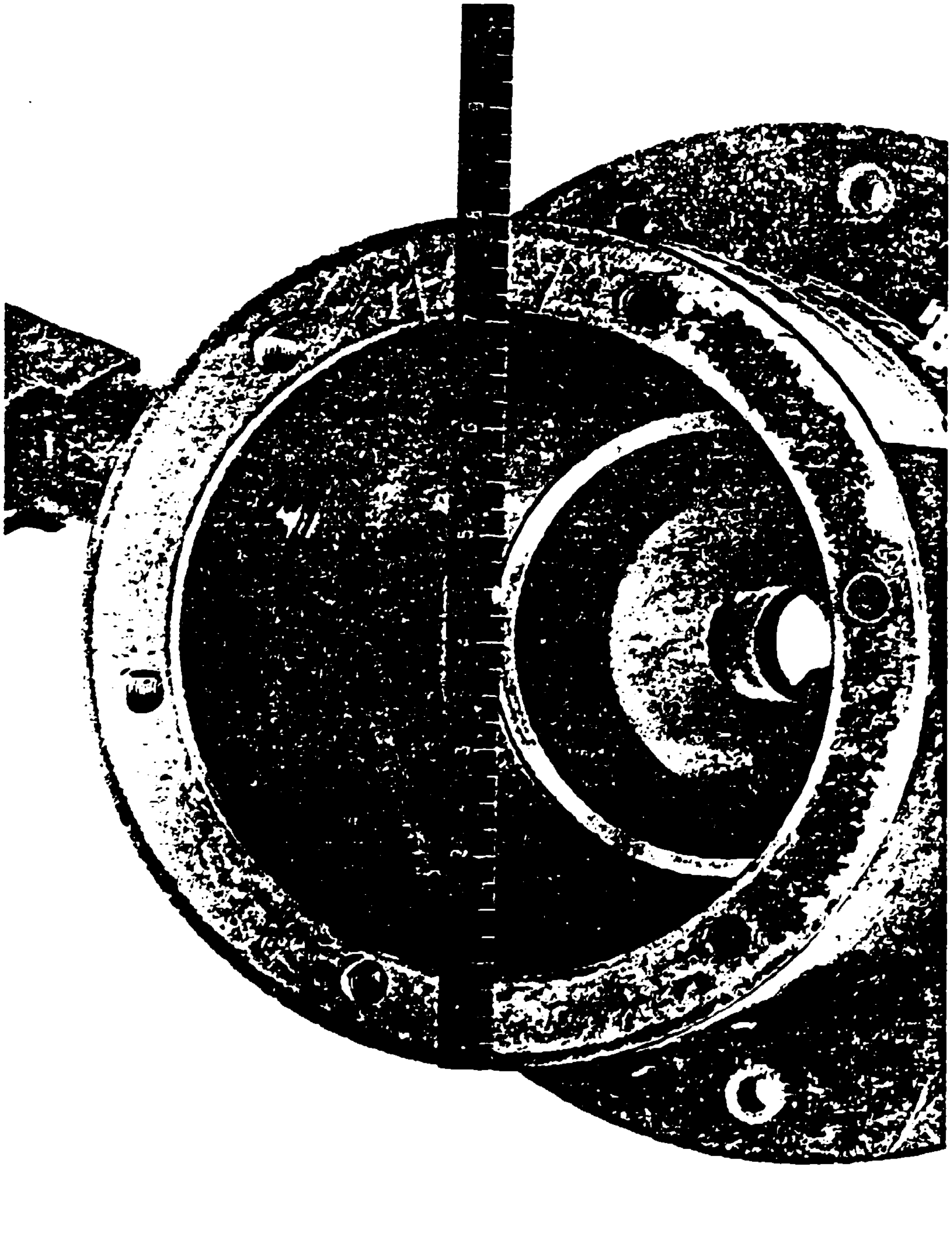

FIGURE 5. PUMP HOUSING

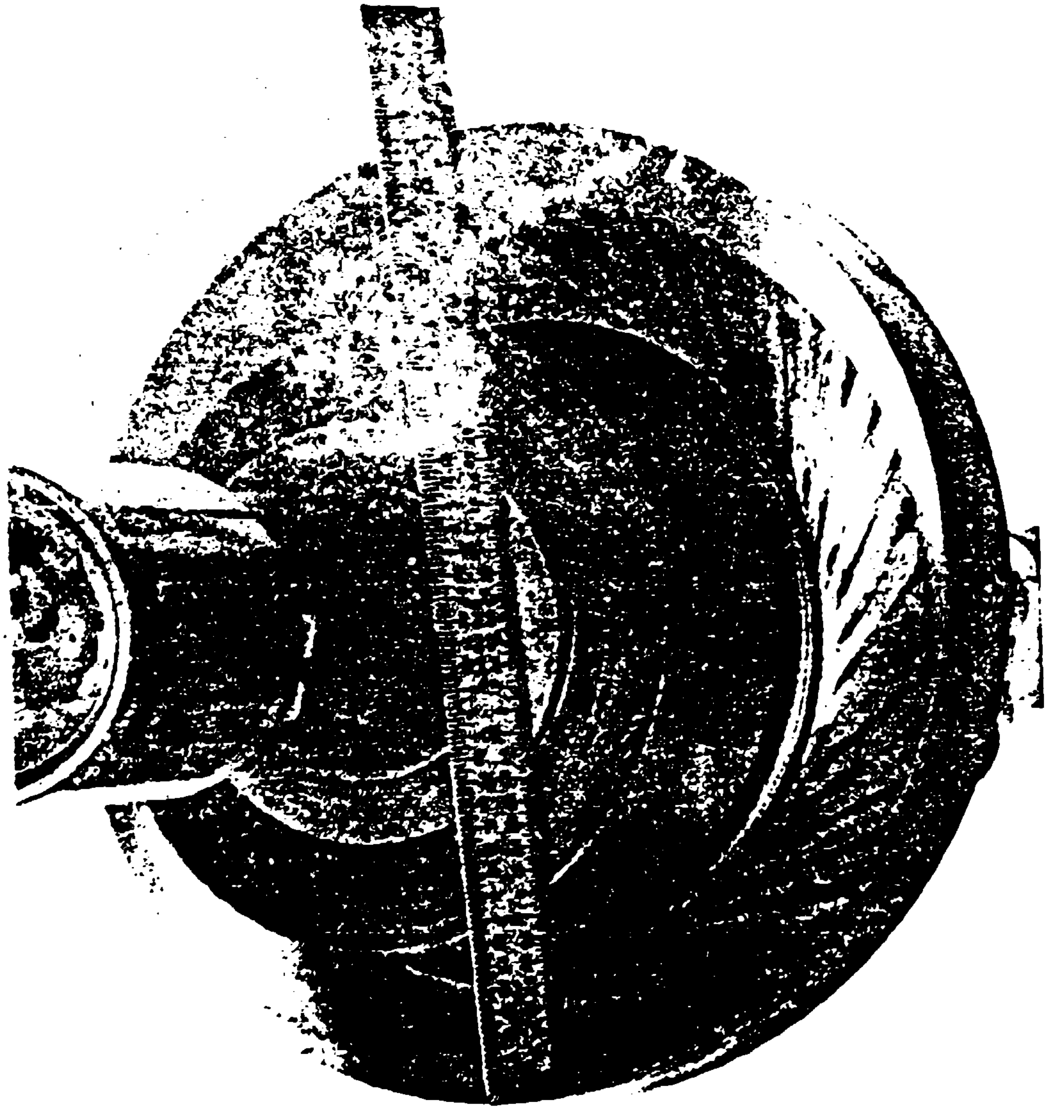

FIGURE 6. PRESSURE BUILD-UP SIDE OF PUMP CAM

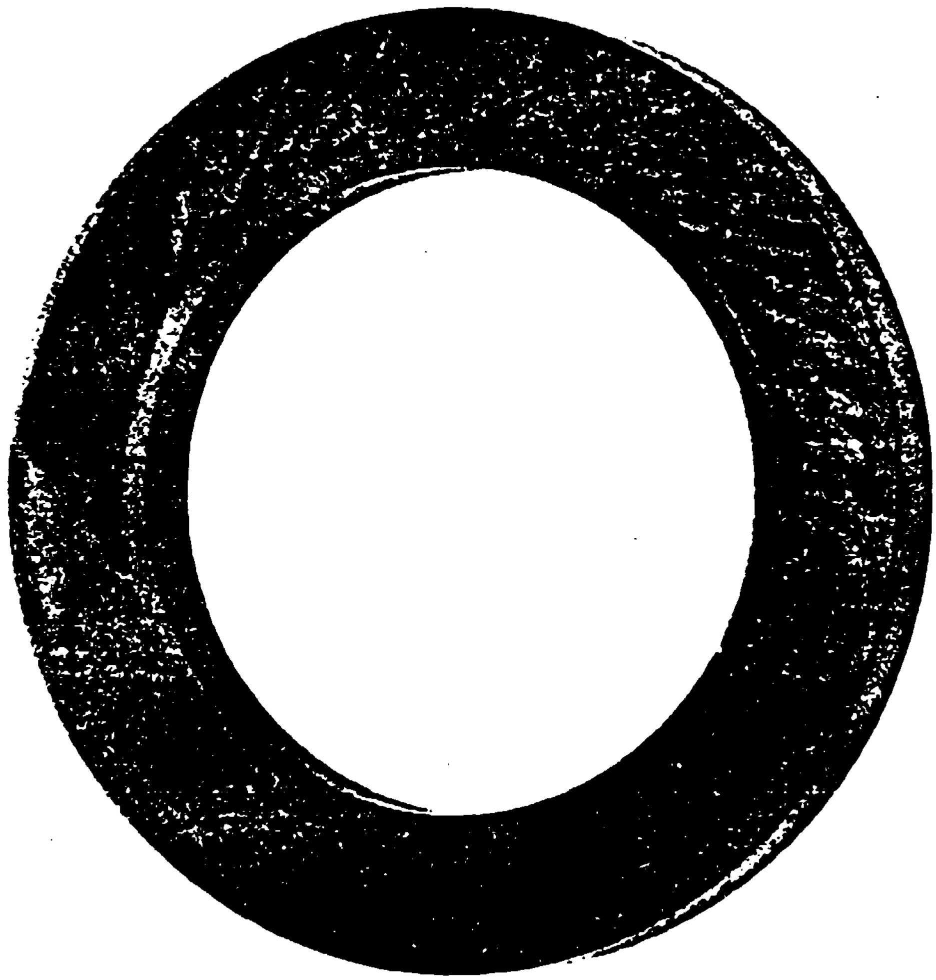

FIGURE 7. CAM TO BEARING WEAR PLATE WHERE IT CONTACTED THE PUMP CAM

TABLE I. VARIATION OF KINEMATIC VISCOSITY (mm^2/s or cSt) WITH TEMPERATURE AND PRESSURE

Pressure MPaG (PSIG)		MIL-H-5606	MIL-H-83282	Nadraul MS-6
Atmospheric				
-54C	(-65)	2000	11,500	2780
-40C	(-40F)	500	2020	1290
38C	(100F)	14.2	18.0	53.9
93C	(200F)	5.4	4.3	17.5
149C	(300F)	2.9	1.8	8.3
204C	(400F)	1.9	1.1	5.0
20.7	(3000)			
38C	(100F)	21.0	23.0	77.6
93C	(200F)	7.5	5.2	23.8
149C	(300F)	4.0	2.2	9.7
55.2	(8000)			
38C	(100F)	40.0	36.0	142.6
93C	(200F)	13.0	7.3	37.6
149C	(300F)	6.6	3.1	10.5

TABLE 2. VARIATION OF DENSITY (g/cc) WITH TEMPERATURE AND PRESSURE

Pressure MPaG (PSIG)	MIL-H-5606	MIL-H-83282	Nadraul MS-6
Atmospheric			
38C (100F)	0.843	0.829	1.0285
93C (200F)	0.802	0.793	0.9797
149C (300F)	0.764	0.756	0.9335
204C (400F)	0.724	0.720	0.8857
20.7 (3000)			
38C (100F)	0.856	0.840	1.0492
93C (200F)	0.818	0.806	1.0063
149C (300F)	0.785	0.773	0.9663
204C (400F)	0.750	0.740	0.9262
55.2 (8000)			
38C (100F)	0.874	0.855	1.0758
93C (200F)	0.840	0.825	1.0375
149C (300F)	0.810	0.795	1.0012
204C (400F)	0.779	0.765	0.9639

TABLE 3. ISOTHERMAL SECANT BULK MODULUS MPaG (PSIG)

MPaG (PSIG)		MIL-H-5606		MIL-H-83282		Nadraul MS-6	
Atmospheric							
38C	(100F)	1288	(186,600)	1322	(191,900)	925	(134,000)
93C	(200F)	933	(135,200)	958	(139,000)	660	(95,700)
149C	(300F)	676	(97,900)	694	(100,700)	485	(70,300)
204C	(400F)	489	(70,900)	503	(73,000)	351	(50,900)
20.7	(3000)						
38C	(100F)	1397	(202,500)	1432	(207,800)	1049	(152,000)
93C	(200F)	1043	(151,100)	1067	(154,900)	785	(113,700)
149C	(300F)	785	(113,800)	796	(115,600)	609	(88,300)
204C	(400F)	599	(86,800)	613	(88,900)	475	(68,900)
55.2	(8000)						
38C	(100F)	1580	(229,000)	1614	(234,300)	1256	(182,000)
93C	(200F)	1225	(177,600)	1250	(181,400)	992	(143,700)
149C	(300F)	968	(140,300)	986	(143,100)	816	(118,300)
204C	(400F)	782	(113,300)	795	(115,400)	682	(98,900)

TABLE 4. ISOTHERMAL TANGENT BULK MODULUS MPaG (PSIG)

MPaG (PSIG)		MIL-H-5606		MIL-H-83282		Nadraul MS-6	
Atmospheric							
38C	(100F)	1288	(186,600)	1322	(191,900)	925	(134,000)
93C	(200F)	933	(135,200)	958	(139,000)	660	(95,700)
149C	(300F)	676	(97,900)	694	(100,700)	485	(70,300)
204C	(400F)	489	(70,900)	503	(73,000)	351	(50,900)
20.7	(3000)						
38C	(100F)	1507	(218,400)	1541	(223,700)	1173	(170,000)
93C	(200F)	1152	(167,000)	1177	(170,800)	909	(131,700)
149C	(300F)	895	(129,700)	913	(132,500)	733	(106,300)
204C	(400F)	709	(102,700)	722	(104,800)	600	(86,900)
55.2	(8000)						
38C	(100F)	1872	(271,400)	1906	(276,700)	1587	(230,000)
93C	(200F)	1518	(220,000)	1542	(223,800)	1323	(191,700)
149C	(300F)	1261	(182,700)	1278	(185,500	1147	(166,300)
204C	(400F)	1074	(155,700)	1087	(157,800)	1014	(146,900)

TABLE 5. ADIABATIC SECANT BULK MODULUS MPaG (PSIG)

MPaG (PSIG)		MIL-H-5606		MIL-H-83282		Nadraul MS-6	
Atmospheric							
38C	(100F)	1584	(229,500)	1626	(236,000)	1095	(158,700)
93C	(200F)	1110	(160,900)	1140	(165,400)	756	(109,500)
149C	(300F)	777	(112,600)	798	(115,800)	543	(78,700)
204C	(400F)	543	(78,700)	558	(81,000)	384	(55,700)
20.7	(3000)						
38C	(100F)	1719	(249,100)	1761	(255,600)	1241	(179,900)
93C	(200F)	1241	(179,800)	1271	(184,400)	900	(130,400)
149C	(300F)	903	(130,900)	924	(134,100)	682	(98,800)
204C	(400F)	665	(96,400)	680	(98,700)	521	(75,500)
55.2	(8000)						
38C	(100F)	1944	(281,700)	1985	(288,100)	1487	(215,500)
93C	(200F)	1458	(211,300)	1488	(215,900)	1137	(164,800)
149C	(300F)	1113	(161,300)	1134	(164,600)	913	(132,300)
204C	(400F)	868	(125,800)	883	(128,200)	746	(108,100)

TABLE 6. ADIABATIC TANGENT BULK MODULUS MPaG (PSIG)

MPaG (PSIG)	MIL-H-5606		MIL-H-83282		Nadraul MS-6	
Atmospheric						
38C (100F)	1584	(229,500)	1626	(236,000)	1095	(158,700)
93C (200F)	1110	(160,900)	1140	(165,400)	756	(109,500)
149C (300F)	777	(112,600)	798	(115,800)	543	(78,700)
204C (400F)	543	(78,700)	558	(81,000)	384	(55,700)
20.7 (3000)						
38C (100F)	1853	(268,600)	1896	(275,200)	1389	(201,300)
93C (200F)	1371	(198,700)	1401	(203,300)	1043	(151,100)
149C (300F)	1029	(149,200)	1050	(152,400)	820	(118,900)
204C (400F)	787	(114,000)	802	(116,300)	656	(95,000)
55.2 (8000)						
38C (100F)	2303	(333,800)	2345	(340,400)	1879	(272,300)
93C (200F)	1806	(261,800)	1835	(266,300)	1517	(219,900)
149C (300F)	1450	(210,100)	1470	(213,400)	1283	(185,900)
204C (400F)	1192	(172,800)	1206	(175,100)	1107	(160,500)

TABLE 7. SPECIFIC HEAT
J/Kg/C (BUT/lb/F)

C (F)	MIL-H-5606	MIL-H-83282	Nadraul MS-6
-18 (0)	1714 (0.410)	1881 (0.450)	1409 (0.337)
38 (100)	1944 (0.465)	2090 (0.500)	1522 (0.364)
93 (200)	2195 (0.525)	2278 (0.545)	1634 (0.391)
149 (300)	2425 (0.580)	2487 (0.595)	1747 (0.418)
204 (400)	2676 (0.640)	2696 (0.645)	1860 (0.445)

TABLE 8. THERMAL CONDUCTIVITY
W/m/C (BTU/ft/hr/F)

C (F)	MIL-H-5606	MIL-H-83282	Nadraul MS-6
-18 (0)	0.140 (0.0810)	0.185 (0.107)	-- --
0 (32)	-- --	-- --	0.152 (0.0878)
38 (100)	0.135 (0.0780)	0.167 (0.0965)	0.144 (0.0832)
93 (200)	0.131 (0.0755)	0.150 (0.0865)	0.136 (0.0784)
149 (300)	0.126 (0.0730)	0.131 (0.0755)	0.128 (0.0738)
204 (400)	0.123 (0.0710)	0.112 (0.0650)	0.120 (0.0693)

TABLE 9. COEFFICIENT OF CUBICAL (THERMAL) EXPANSION

$$\frac{1}{C} \left(\frac{1}{F}\right) \times 10^{+4}$$

C (F)	Nadraul MS-6	
-18 (0)	9.2	(5.1)
38 (100)	8.6	(4.8)
93 (200)	7.9	(4.4)
149 (300)	8.6	(4.8)
204 (400)	11.7	(6.5)

TABLE 10. FLAMMABILITY TEST DATA

Test	Method	MIL-H-5606	MIL-H-83282	Nadraul MS-6
Flash point, C (F)	ASTM D92	99 (210)	224 (435)	277 (530)
Fire point, C (F)	ASTM D92	110 (230)	254 (490)	343 (650)
Auto ignition, C (F)	ASTM D2155	241 (465)	371 (700)	410 (770)
Wick flammability, cycles	ASTM 3150C	1	16	100+
Linear flame propagation rate, cm s^{-1}	Ref. 18	0.76 (10 of 10 tests)	0.33 (10 of 10 tests)	0.0 (10 of 10 tests)
Oxygen index	Modified ASTM D-2863	16.1	18.0	24.0
Hot manifold drip, ignition temp., C (F)	FTMS No. 791b-6053	560 (1040)	327 (620)	538 (1000)
Hot manifold/high pressure spray, ignition temp., C (F)	Modified FTMS No. 791b-6053	>816 (1500)	816 (1500)	--
Low pressure spray ignition	AMS 3150C (SAE)	Increases flame	Carries flame	Extinguishes flame
High pressure spray ignition	AMS 3150C	Ignites and continues to burn	Ignites, self extinguishing	No ignition
Mist flash back, cm (in)	--	7.6 (3.0)	5.8 (2.3)	--

TABLE 10. FLAMMABILITY TEST DATA
(Continued)

Test	Method	MIL-H-5606	MIL-H-83282	Nadraul MS-6
Flame propagation, induction period	MIL-H-83282A	33	Ignites, no propagation in 4 hours	No ignition
Heat of combustion, J kg^{-1} (BTU lb^{-1})	ASTM D240	4.2×10^7 (18000)	4.2×10^7 (18,000)	2.3×10^7 (9700)

TABLE 11. RELATIVE FIRE-RESISTANCE (INCENDIARY GUN-FIRE TEST)*

Fluid	No. of Tests Performed	% Non-Ignition	% Non-Sustained Fires (Average Duration)	% Sustained Fires
			Fires lasting less than 8s	Fires lasting more than 8s
MIL-H-5606	23	0	0	100
MIL-H-83282	78	0	36 (3.25 s)	64
Nadraul MS-5	116	6	85 (0.6 s)	9

* 30 calibre bullet: 0.64 cm (0.25 inch) aluminum striker plate fluid pressure 6.9 MPa (1000 PSI); 400 frames s^{-1}

TABLE 12. LABORATORY AND MECHANICAL PUMP-LOOP WEAR TESTS

Fluid	Four Ball Wear Scar* mm	Piston Pump 20.7 MPa (3000 PSI)	System Temperature C (F)	Pump Life
Phenylmethyl-silicone	>3.0	New York Air Brake (ref 13)	135 (275)	6
Dichlorophenyl-methylsilicone	1.8	New York Air Brake	135 (275)	40
Tetrachlorophenyl-silicone	1.3	--	--	--
MS-5	0.85	Vickers Offset (ref 2)	107 (225)	500+
MS-6	0.78	Vickers In-Line (ref 14)	154 (310)	500+
MIL-H-5606	0.70	New York Air Brake	135 (275)	500+
MIL-H-83282	0.6	New York Air Brake and Vickers Offset (ref 20)	135 (275)	500+

* Test conditions: 75C (167F), 40 kg, 1 h, 1200 RPM, 52100 steel balls

TABLE 13. HYDRAULIC PUMP-LOOP CIRCUIT OPERATING DATA

Average Fluid Temperature		
Reservoir	130C	(265F)
Pump Inlet	130C	(265F)
System	163C	(325F)
Return Line		
Before Heat Exchanger	163C	(325F)
After Heat Exchanger	146C	(295F)
Flow Rate		
Pump Discharge	0.256 dm^3/s	(4.1 gpm)
Average Fluid Pressure		
Pump Discharge	55.2 MPa	(8000 PSI)
Pump Speed		1750 RPM
Total Pump Test Time		502.5 h
Fluid Quantity		
Initial	37.2 dm^3	(37,200 ml)
Added During Test		
New	10.8 dm^3	(10,800 ml)
Reclaimed	4.6 dm^3	(4,600 ml)

TABLE 14. PRESSURE DROP ACROSS FILTER AFTER EACH START-UP

(Pump Speed 1750 PPM; Flow Rate 0.256 dm^3/s (4.1 GPM))

Pump Operating Time Hr, Min	System Temp C (F)	Pump Discharge Pressure MPa (PSI)	Return Line ΔP kPa (PSI)
0	78 (172)	10.3 (1500)	234.6 (34)
3:45	85 (185)	10.3 (1500)	469.2 (68)
*3:45	24 (75)	10.3 (1500)	172.5 (25)
8:25	22 (72)	0 0	345.0 (50)
15:25	21 (70)	0 0	469.2 (68)
15:30	52 (126)	13.8 (2000)	296.7 (43)
22:35	163 (326)	55.2 (8000)	117.3 (17)
*22:35	21 (70)	0 0	331.2 (48)
22:35	43 (110)	13.8 (2000)	241.5 (35)
28:30	38 (100)	13.8 (2000)	372.6 (54)
35:30	163 (325)	55.2 (8000)	441.6 (64)
*35:30	24 (75)	13.8 (2000)	179.4 (26)
43:00	39 (103)	13.8 (2000)	165.6 (24)
49:30	39 (102)	13.8 (2000)	207.0 (30)
55:00	39 (102)	13.8 (2000)	255.3 (37)
59:00	39 (103)	13.8 (2000)	282.9 (41)
60:30	39 (103)	13.8 (2000)	317.4 (46)
66:30	39 (102)	13.8 (2000)	414.0 (60)
74:00	163 (326)	55.2 (8000)	241.5 (35)
*74:00	39 (102)	13.8 (2000)	179.4 (26)
80:30	39 (102)	13.8 (2000)	186.3 (27)
88.00	39 (103)	13.8 (2000)	207.0 (30)
88.00	40 (104)	13.8 (2000)	200.1 (29)
93.30	39 (103)	13.8 (2000)	207.0 (30)
101:00	40 (104)	13.8 (2000)	248.4 (36)
107:00	40 (104)	13.8 (2000)	345.0 (50)
114:00	163 (325)	55.2 (8000)	455.4 (66)
*114:00	40 (104)	13.8 (2000)	138.0 (20)
121:30	40 (104)	13.8 (2000)	172.5 (25)
129.00	40 (104)	13.8 (2000)	193.2 (28)
136:30	40 (104)	13.8 (2000)	276.0 (40)
144:00	40 (104)	13.8 (2000)	414.0 (60)
148:00	40 (104)	13.8 (2000)	586.5 (85)
*154:00	41 (105)	13.8 (2000)	276.0 (40)
160:00	41 (105)	13.8 (2000)	345.0 (50)
168:00	41 (105)	13.8 (2000)	483.0 (70)
176:00	163 (325)	55.2 (8000)	351.9 (51)
*176:00	41 (105)	13.8 (2000)	138.0 (20)
184:00	43 (109)	13.8 (2000)	144.9 (21)
191:30	41 (105)	13.8 (2000)	151.8 (22)

TABLE 14. PRESSURE DROP ACROSS FILTER AFTER EACH START-UP
(Pump Speed 1750 PPM; Flow Rate 0.256 dm^3/s (4.1 GPM)
(Continued)

Pump Operating Time Hr, Min	System Temp C (F)	Pump Discharge Pressure MPa (PSI)	Return Line ΔP kPa (PSI)
199:00	41 (106)	13.8 (2000)	165.6 (24)
207:00	42 (108)	13.8 (2000)	186.3 (27)
215:00	41 (106)	13.8 (2000)	255.3 (37)
223:00	42 (107)	13.8 (2000)	386.4 (56)
231:00	163 (326)	55.2 (8000)	338.1 (49)
*231:00	42 (107)	13.8 (2000)	144.9 (21)
239:00	42 (107)	13.8 (2000)	151.8 (22)
247:00	42 (107)	13.8 (2000)	186.3 (27)
253:30	42 (108)	13.8 (2000)	207.0 (30)
261:30	42 (108)	13.8 (2000)	255.3 (37)
269:30	42 (109)	13.8 (2000)	414.0 (60)
277:00	163 (325)	13.8 (2000)	296.7 (43)
*277:00	43 (110)	55.2 (8000)	138.0 (20)
284:30	46 (115)	13.8 (2000)	117.3 (17)
292:00	44 (112)	13.8 (2000)	331.2 (48)
295:00	46 (115)	13.8 (2000)	386.4 (56)
302:30	163 (325)	55.2 (8000)	331.2 (48)
*302:30	42 (108)	13.8 (2000)	248.4 (36)
310:30	43 (110)	13.8 (2000)	303.6 (44)
318:30	43 (110)	13.8 (2000)	503.7 (73)
323:00	163 (325)	13.8 (8000)	269.1 (39)
*323:00	48 (118)	13.8 (2000)	138.0 (20)
330:00	49 (120)	13.8 (2000)	138.0 (20)
337:00	46 (115)	13.8 (2000)	151.8 (22)
345:00	46 (115)	13.8 (2000)	172.5 (25)
353:00	46 (115)	13.8 (2000)	207.0 (30)
361:00	43 (110)	13.8 (2000)	282.9 (41)
368:30	46 (115)	13.8 (2000)	448.5 (65)
376:00	163 (326)	55.2 (8000)	462.3 (67)
*376:00	43 (110)	13.8 (2000)	165.6 (24)
383:00	43 (110)	13.8 (2000)	234.6 (34)
389:00	163 (326)	13.8 (8000)	662.4 (96)
*389:00	45 (113)	13.8 (2000)	303.6 (44)
395:30	163 (326)	55.2 (8000)	579.6 (84)
*395:30	42 (108)	13.8 (2000)	165.6 (24)
400:00	48 (118)	13.8 (2000)	234.6 (34)
433:00	163 (325)	55.2 (8000)	151.8 (22)
*433:00	47 (116)	13.8 (2000)	414.0 (60)
452:30	163 (326)	55.2 (8000)	207.0 (30)
*452:30	47 (116)	13.8 (2000)	276.0 (40)
460:00	47 (116)	13.8 (2000)	338.1 (49)

TABLE 14. PRESSURE DROP ACROSS FILTER AFTER EACH START-UP
(Pump Speed 1750 PPM; Flow Rate 0.256 dm^3/s (4.1 GPM)
(Continued)

Pump Operating Time Hr, Min	System Temp C (F)	Pump Discharge Pressure MPa (PSI)	Return Line ΔP kPa (PSI)
467:00	48 (118)	13.8 (2000)	427.8 (62)
474:00	59 (138)	13.8 (2000)	414.0 (60)
476:00	44 (112)	13.8 (2000)	641.7 (93)
484:00	163 (325)	55.2 (8000)	310.5 (45)
*484:00	46 (115)	13.8 (2000)	358.8 (52)
491:30	46 (115)	13.8 (2000)	621.0 (90)
499:00	162 (324)	55.2 (8000)	207:0 (30)
*499:00	49 (120)	13.8 (2000)	434.7 (63)
502:30	163 (325)	55.2 (8000)	96.6 (14)

* Filter Element Replaced

TABLE 15. PUMP TEST FLUID SAMPLE PROPERTIES

Sample Test Hours	Viscosity(1), 38C (100F) mm^2/s or cSt	Four-Ball Wear Scar(2), mm 204C (400F)
0	52.7	1.10
25	53.5	1.21
50	53.5	1.11
75	53.4	1.06
100	53.7	1.08
150	53.5	1.08
200	53.3	1.08
250	53.7	1.08
275	53.2	1.12
300	53.0	1.11
350	53.9	1.16
400	52.5	1.15
450	52.1	1.17
500	52.0	1.19

(1) ASTM D445

(2) ASTM D2266 40 Kg, 1200 RPM, 1 h, 52100 steel balls

TABLE 16. VAPOR PRESSURE
Pa (Torr)

C (F)	MIL-H-5606	MIL-H-83282	Nadraul MS-6
-18 (0)	-	-	8.0×10^{-5} (6.0×10^{-7})
38 (100)	13.3 (0.1)	-	2.7×10^{-2} (2.0×10^{-4})
93 (200)	399 (3)	638 (4.8)	1.1 (8.4×10^{-3})
149 (300)	5054 (38)	3325 (25)	20 (0.15)
204 (400)	27,930 (210)	11,970 (90)	80 (0.6)

TABLE 17. FOAMING TENDENCY 25C (77F)
ASTM D892

	MIL-H-5606	MIL-H-83282	Nadraul MS-6	Nadraul MS-6 with 100 PPM Anti-Foam Agent
ml of foam after 5 min. aeration	50	35	400	0
ml of foam after 10 min. settling period	0	0	0	0

TABLE 18. STABILITY AND CORROSION TESTS ON NADRAUL MS-6

Property	Test Method	Value	
Hydrolytic Stability 48h, 107C (225F)	ASTM D2619		
Δwt. of Cu, mg		0.00	
ΔViscosity, 38C (100F) %		-0.017	
Total acidity H_2O layer, mg KOH		1.94	
Acid No. organic layer, mg KOH/g		0.03	
Thermal Stability 168h, 204C (400F)	FTS-791-5308 modified to use N_2 instead of air	With Metals	No Metals
ΔViscosity, 38C (100F), percent		+4.7	+7.1
Acid No. Change, mgKOH/g		+0.08	+0.18
Insolubles or gum		None	None
Shear Stability	MIL-H-5606D		
ΔViscosity, 38C (100F), %	Paragraph 4.7.4	+2.0	
Acid No Increase, mgKOH/g		0.00	
Pour Point, C (F)	ASTM D97	<-62	(<-80)
Cloud Point, C (F)	ASTM D97	None down to -62 (-80)	
Oxidation-Corrosion 168h	FTS-791-5308	204C (400F)	177C (350F)
ΔViscosity, 38C (100F), percent		+13.2	+0.02
Acid No. Change, mgKOH/g		+0.08	+0.03
Metal Wt. Change, mg cm^{-2}			
Cu		-1.0	-0.33
Al		+0.02	-0.03
Mg		-0.02	-0.04
Fe		+0.01	-0.02
Ag		+0.04	----
Insolubles or gum		None	None
Copper Corrosion 204C (400F), 100h	ASTM D130	Pass	
Streaming Potential Wall Current at 20.7 MPa (3000 PSI), amps	Ref (19)	$<10^{-12}$	

APPENDIX A

STATISTICS ON U. S. NAVAL AIRCRAFT HYDRAULIC FLUID INDUCED FIRES

SOURCE: Computer listing of all U. S. Naval Aircraft non-combat fires for the period 1965 through 1975 obtained from the Naval Safety Center, Norfolk, Virginia. The tables were derived from authors' interpretation after reading each narrative.

TABLE A1. USN AIRCRAFT FIRES (NON-COMBAT)

(1965 - 1975)

TOTAL. 2500 (approx.)

Hydraulic Fluid Induced:

Actual: 101 (4%)

Suspected: 33 (1.3%)

TABLE A2. USN YEARLY AIRCRAFT HYDRAULIC FLUID FIRES

	65	66	67	68	69	70	71	72	73	74	75	TOTAL
MAJOR	0	4	2	9	5	4	1	0	4	0	0	29
MINOR	6	4	3	6	4	1	0	0	1	0	1	26
INCIDENT	1	2	3	6	5	3	9	3	6	4	4	46
TOTAL	7	10	8	21	14	8	10	3	11	4	5	101

TABLE A3. USN AIRCRAFT TYPE HYDRAULIC FLUID FIRES

A/C Type	Major	Minor	Incident	Total
Fighter	10	18	14	42
Attack	14	1	9	24
Helicopter	1	5	11	17
Antisubmarine	2	1	2	5
Cargo	0	0	4	4
Airborne Early Warning	1	0	3	4
Patrol	0	0	2	2
Utility	1	0	1	2
Trainer	0	1	0	1
TOTAL	29	26	46	101

TABLE A4. USN AIRCRAFT HYDRAULIC FLUID FIRES BY PART OF AIRCRAFT

Part of A/C	Major	Minor	Incident	Total
Engine	9	8	16	33
Wheel	3	3	11	17
Tailsection	4	5	4	13
Tailhook	3	4	0	7
Rotor Brake	1	3	3	7
Bomb Bay	5	0	0	5
Equipment Compartment	0	0	3	3
Wheel Well	2	0	0	2
Refueling Drouge	0	0	2	2
Auxiliary Air Door	0	0	2	2
Cockpit	0	1	1	2
Forward Fuselage	0	0	1	1
Wing	1	0	0	1
Undetermined	1	2	3	6
TOTAL	29	26	46	101

TABLE A5. USN AIRCRAFT HYDRAULIC FLUID FIRES BY PHASE OF OPERATION

	Major	Minor	Incident	Total
Parked	4	10	17	31
Cruise	3	4	11	18
Maintenance Run	7	7	4	18
Landing	4	1	6	11
Climb	7	1	3	11
Taxi	3	3	4	10
Takeoff	1	0	1	2
Final Approach	0	0	0	0
TOTAL	29	26	46	101

TABLE A6. USN AIRCRAFT HYDRAULIC FLUID FIRES BY COMBINED PART OF AIRCRAFT AND PHASE OF OPERATION

Part of A/C	Phase of Operation	Major	Minor	Incident	Total
Engine	Parked	0	4	10	14
Engine	Cruise	3	2	3	8
Wheel	Landing	1	1	5	7
Tailsection	Maintenance Run	0	5	2	7
Wheel	Taxi	0	2	4	6
Rotor Brake	Parked	1	2	2	5
Engine	Climb	2	1	1	4
Bomb Bay	Maintenance Run	4	0	0	4
Tailsection	Climb	3	0	0	3
Tailhook	Maintenance Run	2	1	0	3
Tailhook	Parked	0	3	0	3
Wheel	Parked	1	0	2	3
Rotor Brake	Cruise	0	1	1	2
Engine	Maintenance Run	1	0	1	2
Engine	Takeoff	1	0	1	2
Refueling Drouge	Cruise	0	0	2	2
Undetermined	Cruise	0	1	1	2
Engine	Landing	2	0	0	2
Undetermined	Parked	0	0	2	2
Wheel Well	Taxi	1	0	0	1
Tailsection	Taxi	1	0	0	1
Wing	Taxi	1	0	0	1
Engine	Taxi	0	1	0	1
Tailhook	Landing	1	0	0	1
Tailsection	Landing	0	0	1	1
Wheel	Climb	1	0	0	1
Aux. Air Door	Climb	0	0	1	1
Equipment Compt.	Climb	0	0	1	1
Equipment Compt.	Cruise	0	0	1	1
Tailsection	Cruise	0	0	1	1
Aux. Air Door	Cruise	0	0	1	1
Fwd. Fuselage	Cruise	0	0	1	1
Cockpit	Maintenance Run	0	0	1	1
Equipment Compt.	Parked	0	0	1	1
Cockpit	Parked	0	1	0	1
Bomb Bay	Parked	1	0	0	1
Wheel Well	Parked	1	0	0	1
Undetermined	Climb	1	0	0	1
Undetermined	Maintenance Run	0	1	0	1
	TOTAL	29	26	46	101

TABLE A7. USN AIRCRAFT HYDRAULIC FLUID FIRES BY PHASE OF OPERATION WITH PART OF AIRCRAFT

Parked	Major	Minor	Incident	Total
Engine	0	4	10	14
Rotor Brake	1	2	2	5
Tailhook	0	3	0	3
Wheel	1	0	2	3
Equipment Compt.	0	0	1	1
Cockpit	0	1	0	1
Bomb Bay	1	0	0	1
Wheel Well	1	0	0	1
Undetermined	0	0	2	2
TOTAL	4	10	17	31
Cruise				
Engine	3	2	3	8
Refueling Drouge	0	0	2	2
Rotor Brake	0	1	1	2
Equipment Compt.	0	0	1	1
Tailsection	0	0	1	1
Aux. Air Door	0	0	1	1
Fwd. Fuselage	0	0	1	1
Undetermined	0	1	1	2
TOTAL	3	4	11	18
Maintenance Run				
Tailsection	0	5	2	7
Bomb Bay	4	0	0	4
Tailhook	2	1	0	3
Engine	1	0	1	2
Cockpit	0	0	1	1
Undetermined	0	1	0	1
TOTAL	7	7	4	18
Landing				
Wheel	1	1	5	7
Engine	2	0	0	2
Tailhook	1	0	0	1
Tailsection	0	0	1	1
TOTAL	4	1	6	11

TABLE A7. USN AIRCRAFT HYDRAULIC FLUID FIRES BY PHASE OF OPERATION WITH PART OF AIRCRAFT (continued)

Climb	Major	Minor	Incident	Total
Engine	2	1	1	4
Tailsection	3	0	0	3
Wheel	1	0	0	1
Aux. Air Door	0	0	1	1
Equipment Compt.	0	0	1	1
Undetermined	1	0	0	1
TOTAL	7	1	3	11
Taxi				
Wheel	0	2	4	6
Wheel Well	1	0	0	1
Tailsection	1	0	0	1
Wing	1	0	0	1
Engine	0	1	0	1
TOTAL	3	3	4	10
Takeoff				
Engine	1	0	1	2
TOTAL	1	0	1	2
TOTAL	29	26	46	101

TABLE A8. USN AIRCRAFT HYDRAULIC FLUID FIRES BY PART OF AIRCRAFT WITH PHASE OF OPERATION

Engine	Major	Minor	Incident	Total
Parked	0	4	10	14
Cruise	3	2	3	8
Climb	2	1	1	4
Landing	2	0	0	2
Maintenance Run	1	0	1	2
Takeoff	1	0	1	2
Taxi	0	1	0	1
TOTAL	9	8	16	33

Wheel	Major	Minor	Incident	Total
Landing	1	1	5	7
Taxi	0	2	4	6
Parked	1	0	2	3
Climb	1	0	0	1
TOTAL	3	3	11	17

Tailsection	Major	Minor	Incident	Total
Maintenance Run	0	5	2	7
Climb	3	0	0	3
Taxi	1	0	0	1
Landing	0	0	1	1
Cruise	0	0	1	1
TOTAL	4	5	4	13

Tailhook	Major	Minor	Incident	Total
Maintenance Run	2	1	0	3
Parked	0	3	0	3
Landing	1	0	0	1
TOTAL	3	4	0	7

Rotor Brake	Major	Minor	Incident	Total
Parked	1	2	2	5
Cruise	0	1	1	2
TOTAL	1	3	3	7

Bomb Bay	Major	Minor	Incident	Total
Maintenance Run	4	0	0	4
Parked	1	0	0	1
TOTAL	5	0	0	5

TABLE A8. USN AIRCRAFT HYDRAULIC FLUID FIRES BY PART OF AIRCRAFT WITH PHASE OF OPERATION (continued)

Equipment Compt.	Major	Minor	Incident	Total
Climb	0	0	1	1
Cruise	0	0	1	1
Parked	0	0	1	1
TOTAL	0	0	3	3
Wheel Well				
Taxi	1	0	0	1
Parked	1	0	0	1
TOTAL	2	0	0	2
Refueling Drouge				
Cruise	0	0	2	2
Aux. Air Door				
Climb	0	0	1	1
Cruise	0	0	1	1
TOTAL	0	0	2	2
Cockpit				
Maintenance Run	0	0	1	1
Parked	0	1	0	1
TOTAL	0	1	1	2
Fwd. Fuselage				
Cruise	0	0	1	1
Wing				
Taxi	1	0	0	1
Undetermined				
Parked	0	0	2	2
Cruise	0	1	1	2
Climb	1	0	0	1
Maintenance Run	0	1	0	1
TOTAL	1	2	3	6
TOTAL	29	26	46	101

TABLE A9. USN AIRCRAFT HYDRAULIC FLUID FIRES BY PART OF AIRCRAFT AND MODEL OF AIRCRAFT

Engine	Major	Minor	Incident	Total
H-46	0	2	7	9
F-4	4	2	2	8
A-4	4	0	1	5
F-8	0	2	2	4
A-6	1	0	1	2
F-9	0	1	0	1
T-2	0	1	0	1
U-16	0	0	1	1
C-2	0	0	1	1
H-3	0	0	1	1
TOTAL	9	8	16	33

Wheel	Major	Minor	Incident	Total
F-8	0	3	0	3
S-2	0	0	2	2
A-7	1	0	1	2
A-6	0	0	2	2
U-11	1	0	0	1
A-5	1	0	0	1
P-2	0	0	1	1
P-3	0	0	1	1
A-3	0	0	1	1
C-117	0	0	1	1
C-118	0	0	1	1
C-130	0	0	1	1
TOTAL	3	3	11	17

Tailsection	Major	Minor	Incident	Total
F-8	1	3	3	7
F-9	3	2	1	6
TOTAL	4	5	4	13

Tailhook	Major	Minor	Incident	Total
F-8	2	4	0	6
A-4	1	0	0	1
TOTAL	3	4	0	7

Rotor Brake	Major	Minor	Incident	Total
H-46	1	2	0	3
H-34	0	1	1	2
H-3	0	0	2	2
TOTAL	1	3	3	7

TABLE A9. USN AIRCRAFT HYDRAULIC FLUID FIRES BY PART OF AIRCRAFT AND MODEL OF AIRCRAFT (Continued)

Bomb Bay	Major	Minor	Incident	Total
A-5	5	0	0	5
Equipment Compt.				
E-2	0	0	3	3
Wheel Well				
S-2	1	0	0	1
S-3	1	0	0	1
TOTAL	2	0	0	2
Refueling Drouge				
A-7	0	0	2	2
Aux. Air Door				
F-4	0	0	2	2
Cockpit				
S-2	0	1	0	1
F-4	0	0	1	1
TOTAL	0	1	1	2
Fwd. Fuselage				
F-4	0	0	1	1
Wing				
E-2	1	0	0	1
Undetermined				
F-8	1	1	3	5
F-4	0	1	0	1
TOTAL	1	2	3	6
TOTAL	29	26	46	101

TABLE A10. USN AIRCRAFT HYDRAULIC FLUID FIRES
BY COMPONENT INVOLVED

Component	Major	Minor	Incident	Total
Line	22	13	16	51
Seal	0	3	13	16
Fitting	5	5	5	15
Pump	1	2	3	6
Other	1	3	6	10
Undetermined	0	0	3	3
TOTAL	29	26	46	101

TABLE A11. USN HYDRAULIC FLUID FIRES BY IGNITION SOURCE

Ignition Source	Major	Minor	Incident	Total
Hot Surface	18	18	32	68
Electrical	8	2	6	16
Inc.. diary	0	0	2	2
Undetermined	3	6	6	15
TOTAL	29	26	46	101

TABLE A12. USN AIRCRAFT HYDRAULIC FLUID FIRES ABOARD CARRIERS

MAJOR	MINOR	INCIDENTS	TOTAL
4	0	4	8

TABLE A13. USN AIRCRAFT HYDRAULIC FLUID FIRES

MAJOR

	Total A/C Loss	Substantial Damage	Total
Actual	7	22	29
Suspected	16	9	25
	Minor	Incident	Total
Actual	26	46	72
Suspected	3	5	8
			134

DEFINITION OF TERMS

MAJOR: Total loss or substantial aircraft damage.

MINOR: Minor aircraft damage.

INCIDENT: Limited or no aircraft damage.

TAXI: Movement of aircraft on ground or flight deck except takeoff and landing.

TAKEOFF: Ground or flight deck movement from brake release to liftoff.

CLIMB: Initial climb after takeoff.

CRUISE: Flight between climb and final approach.

FINAL APPROACH: Flight from landing configuration to touch-down.

LANDING: Ground or flight deck movement from touch-down to departing runway.

PARKED: Stopped on ground or flight deck.

MAINTENANCE RUN: Maintenance check of aircraft on ground with power on.

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